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Block 13: Supplementary Note

Remote sub-diffraction imaging with femtosecond laser filaments

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Achieving super-resolution has become a scientific imperative for remote imaging of objects and scenes needing increased detail and has motivated the development of various laser-based techniques. We demonstrate a scheme which achieves subdiffraction imaging of remote objects by using femtosecond laser filaments. The use of laser filaments for imaging is destined to have applications in many environments.

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Ever since the invention of the telescope, many techniques for seeing at a distance have been developed, even up to the present. Normally these are limited by diffraction, which is a consequence of the wave properties of light that cause it to spread as it propagates. One way to overcome this limit is to illuminate the target with a focused beam from a source, like a laser, that is in the proximity of the target. However, the deployment of a distant laser source is usually not practical, and so an alternative is needed. Here we assert that laser-triggered filaments can provide the high-resolution illumination spots needed to achieve practical long-range subdiffraction imaging.

Filamentation occurs when an intense femtosecond laser pulse is self-focused to create an intensity large enough to ionize the material. Once this threshold is reached, the laser beam is self-guided, and its size is determined by the interplay between Kerr self-focusing and defocusing from low-density plasma. Hence the size of the filaments is not limited by the aperture of an optical system [1] which would ordinarily determine the diffraction-limited laser spot size. The intensity and diameter of a self-guided filament remain constant as it propagates. This means the depth of field may be several orders of magnitude greater than that of a conventional imaging system, as it is determined by the length of the filament.

The use of femtosecond pulses with negative prechirping has demonstrated the ability to create these filaments at a long distance from the source [2–4]. This technique has already been considered for long-range sensing, for example, ionization of particular chemicals in the air for remote threat detection [1,5], remotely guiding real lightning bolts along safe discharge paths [6], or possibly the production of backward propagating lasers for long-range high-resolution spectroscopy [7,8]. In remote imaging and sensing, beating the diffraction limit by using nonlinearities of the intervening medium between object and image is an approach that has been largely neglected. Several related techniques have been demonstrated, such as two-photon interference ghost imaging [9], and imaging using Bessel beams [10].

In a proof-of-principle experiment, we demonstrate remote imaging with resolution at least an order of magnitude greater than that allowed by diffraction by using femtosecond laser filaments in water. Our experimental setup is shown in Fig. 1. We use a Ti:Sapphire regenerative amplifier (Legend Elite Coherent: 1 kHz rep. rate, 4 mj/pulse) seeded by a Coherent Micra-5 Ti:Sapphire Oscillator (80 MHz rep. rate, 470 mW). The amplifier spectrum is centered at 800 nm, and the pulse is 34 fs FWHM. The power is attenuated by neutral density filters, while the iris diameter is $D = 2$ mm. The measured FWHM of the spatial beam profile at the target is around 1.4–1.6 mm. The beam power after the iris is 203 mW, which is sufficient to generate a single filament in water. In order to establish a stable single filament, we adjust the chirp of the pulse by varying the compressor setting of the amplifier; the beam power remains constant.

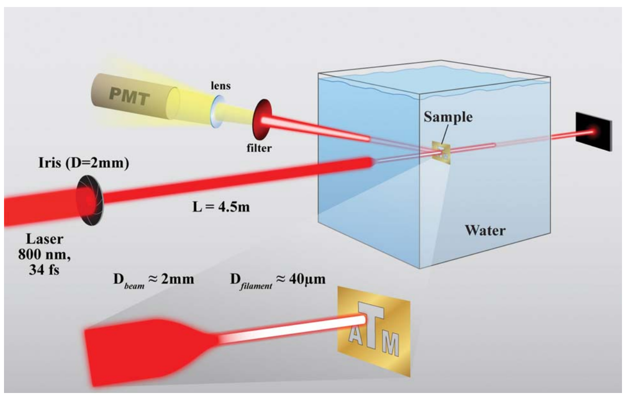

Fig. 1. (Color online) Experimental setup. Iris diameter is $D = 2$ mm; it is $L = 4.5$ mm away from the target. The diffraction limit is $\delta = 1.22\lambda L/D = 2.19$ mm. Diameter of the filament is about 40 μm, which is 50 times smaller than the diffraction limit δ. The target (ATM logo) is inside a water tank. Photomultiplier tube (PMT) collects the back-scattered light in order to reconstruct the image. High-pass optical filter is used to block the scattered 800 nm light from the energy reservoir of the filament.

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The target is placed in a water tank $L \approx 4.5$ m distant from the iris. Back-scattered light from the sample is collected by a photomultiplier tube (PMT). A high-pass optical filter is used to block the 800 nm back-scattered light from the energy reservoir of the filament while allowing the white-light generated in the filament core to be detected. The diameter of the iris D and the distance L determine the diffraction limit to be $\delta = 1.22\lambda L/D = 2.19$ mm. The diameter of the filament is around 40 μm (estimated by knife-edge transmission measurements; not shown), which together with the scan step determines the resolution of the image. In order to compare images with and without filaments, we stretch the laser pulse in time, so that no filaments can be generated when the light propagates through the water tank. All other conditions, including the incident beam size and pulse energy, are kept the same as the image without a filament is recorded.

Our first target consists of two wires which are 150 μm in diameter and separated by about 400 μm. As shown in Fig. 2(a), the two wires are clearly resolved with the formation of a stable single filament; resolution of the wires disappears when the image is constructed without the filament [Fig. 2(b)]. The target is attached to a two-dimensional (2D) translation stage. The scan steps are 20 μm in the horizontal direction and 50 μm in the vertical direction. Hence the pixel size of the image is 20×50 μm. The images have been digitally processed with interpolation. Figures 2(c) and 2(d) show the cross-sections of the 2D scans in Figs. 2(a) and 2(b), respectively. The cross-sections coincide well with the theoretical convolutions (red curves).

Our second target is the Texas A&M University logo (ATM). The stroke width of each letter in the logo is about 300 μm, less than the diffraction limit of the system (2.19 mm). The letters are sculpted onto a transparency film [Fig. 3(d)]. Figure 3(a) is the retrieved image of the logo using a stable single filament, while Fig. 3(b) shows

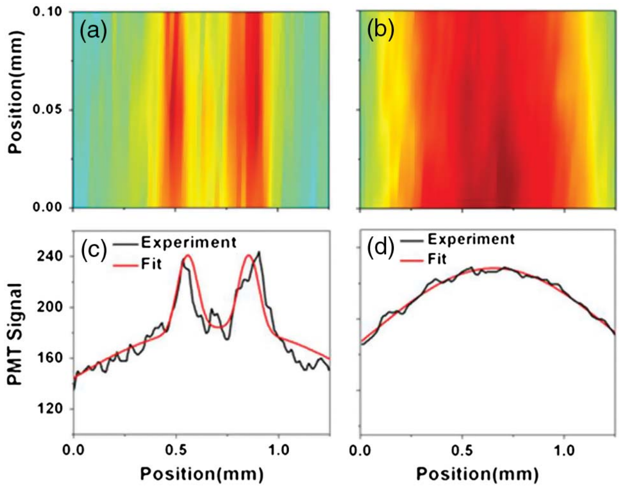

Fig. 2. (Color online) Remotely retrieved images of two wires. Wires are 150 μm in diameter and are separated by about 400 μm. (a) and (b) are the reconstructed images with and without a stable single filament, respectively. (c) and (d) are the cross-sections of images (a) and (b), respectively. Black curves are the experimental data and the red curves are the theoretical fits.

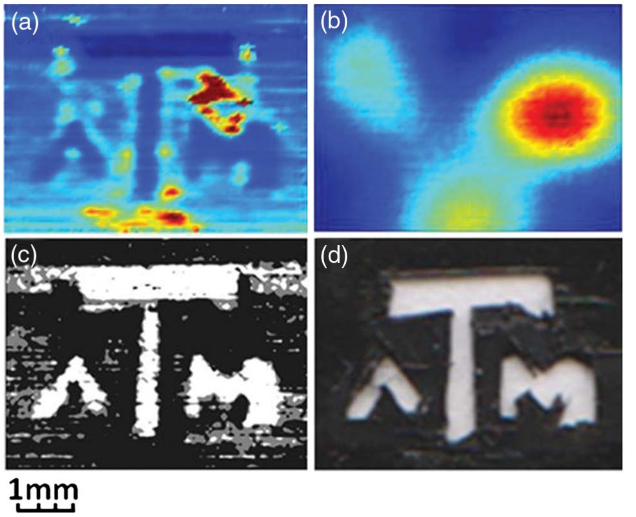

Fig. 3. (Color online) Remotely retrieved images of the TAMU logo (ATM) with (a) and without (b) a stable filament. Strokes of the letters are about 300 μm thick, smaller than the diffraction limit of our optical setup. With the filament, the ATM logo can be imaged clearly, while without a filament, the letters cannot be resolved. (c) Digitally processed image in (a). (d) Microphotograph of the logo sculpted onto the transparency.

the image obtained without the use of filaments. The pixel size of these images is 50×50 μm, and they have been digitally processed with interpolation as well. Our results clearly show that the subdiffraction logo pattern can be resolved with a single filament. Figure 3(c) digitally enhances the contrast of Fig. 3(a).

The relatively small distances (and moderate laser powers) at which filament formation occurs in water render it useful for controlled studies of filament propagation in the laboratory. For long-range imaging in the atmosphere, the performance may be projected from our data with appropriate scaling [11]. The total number of molecules that a beam encounters, and hence the total linear dispersion per unit length, is proportional to the molecular density, which is three orders of magnitude greater for liquids than for gases under similar conditions. Therefore, each 1 cm of propagation in water, in terms of dispersion, will roughly correspond to 10 m in air. Nonlinear refraction will also scale with the molecular density, and, in addition, with laser power, so that more powerful laser sources will have to be used in atmospheric experiments. Based on the power of available lasers, we envision subdiffraction imaging in air that might perform kilometers away from the target [12].

For such long-range applications, control of filament formation and propagation is paramount. Here we note that filaments are robust and can maintain shape while propagating through rough media, turbulence, and aerosol perturbations which tend to spread conventional beams [13,14]. Significantly, even if it is not possible to adequately stabilize the filament positions, high-resolution images can still be constructed using random filament positions by precisely determining the location of each filament flash in the image plane, for example computing the centroids in a manner analogous to the popular stochastic subwavelength imaging technique [15–17].

In conclusion, we demonstrate a remote-imaging method which retrieves images having resolution at least an order of magnitude greater than the diffraction limit. Femtosecond laser filaments illuminate a remote target and the backscattered light is collected to construct an image. In particular, our demonstration experiment is directly applicable to high-altitude airborne imaging of small objects beneath the ocean surface. Such remote imaging schemes are relevant to applications in which high-resolution must be obtained at a great distance and may find use both underwater and in the atmosphere.

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